

PARALLEL ACTIVE POWER FILTER BASED ON SYNCHRONOUS REFERENCE FRAME ALGORITHM

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Abstract: In this paper a 33kVA Active Power Filter (APF) prototype based on the synchronous $d-q$ reference frame (SRF) control method, well-known in the motor drives industry, is presented. The proportional-integral controllers are used for the voltage and current control loops. The proposed scheme employs a pulse-width modulation (PWM) voltage-source inverter. The APF prototype has been developed in order to meet the harmonics limits imposed by the IEEE Standard 519 [1] under all supply and load conditions. The main project objectives have been to design, realize and test an active power filter. In particular, the new apparatus had to have the following features: to control the active filter in a closed loop manner so as to actively shape the source current into the sinusoid; to compensate transient and harmonic components of the load current. The performance evaluation has been done on the basis of the %THD in the load current and the compensated mains current. Experimental results have shown that the APF system meets the IEEE 519 harmonic current limits in the supply.

Keywords: Active power filter, synchronous reference frame, harmonics compensation

1. INTRODUCTION

The increasing use of high power non-linear loads (adjustable speed drives, ac/dc rectifiers etc.) has caused an increase of harmonic pollution and of the reactive power demand in the operation of power systems. The current harmonics generation is a consequence of a line commutated rectifiers switched operation and of the harmonics generating loads. Current harmonics result in a distorted voltage and additional losses in the distribution network. The strongest sources of harmonic distortion are the variable frequency motor drives type loads. These loads not only have the potential to produce harmonic distortion, but the amount varies with loading. For electrical drive systems, the voltage distortion causes thermal stress and torque ripple. These may lead to premature ageing of the electrical machines, cables and transformers. The goal of the compensation is to eliminate the components of power that do not contribute to the net transfer of energy from the source to the load. The ideal situation is that the waveforms of voltage and current in the line are both sinusoids and in phase. The well-known conventional passive filters were used in the past, but the passive filters were tuned for specific harmonics and, therefore, the performance of the passive filters was strongly dependent on the system impedance (which depended on the distribution network configuration and the loads) at the harmonic frequencies [2]. The source impedance was not accurately known and varied with the system configuration, affecting filtering characteristics. Parallel resonance between a source and a passive filter caused amplification of harmonics currents on the source side at specific frequencies. To obtain adequate filtering performance of the passive filters a difficult design has been necessary. At the same time, the passive filters did not provide a dc voltage regulation and required bulky reactive components (capacitor, inductance). An alternative is to use active power filter which provides a regulated dc output voltage. Active filters consisting of voltage or current source pulse width modulated (PWM) inverters have been studied to overcome the afore-mentioned disadvantages inherent in passive filters. The most harmonic distortion limits are specified by the IEEE Standard 519 for current harmonics

at the point of common coupling, and by the IEC-555 [3] for individual loads absolute limits. Various active power filter configurations and control strategies have been proposed and developed [4]-[9]. Parallel active filters have been recognized as a valid solution to current harmonic and reactive power compensation of non-linear loads [10],[11]. A shunt active filter is controlled to actively shape a compensating current that cancels the distortion of the load current, so that the source current becomes sinusoidal. In this paper, the most commonly used control method for APFs Synchronous Reference Frame (SRF) [7],[11] or “ $d-q$ ” reference frame) is discussed.

2. SYSTEM CONFIGURATION

Fig. 1 shows a power circuit of the active filter used for experiment. It consists of a three-phase voltage-fed PWM inverter using six IGBTs, three interfacing inductors and a dc bus capacitor. The active filter connected in parallel to the end bus of the line is controlled in such a way as to draw the compensating current to the line (i_F), as shown in Fig. 2.

The main project objectives have been to design, realize and test an APF converter. In particular the new apparatus had to have the following features: (i) To control the active filter in a closed loop manner so as to actively shape the source current into the sinusoid; (ii) To compensate transient and harmonic components of the load current.

The strategies adopted to achieve the above objectives have been the Instantaneous Active and Reactive Current Component Method (IARC) [7].

Table 1. The parameters design specifications.

Ratings and parameters	APF
Rated power	$S_N = 33 \text{ kVA}$
Rated mains voltage	$V_{a,b,c} = 230 \text{ V}$
Rated mains frequency	$f = 50 \text{ Hz}$
Rated input current	$I_{LDC} = 48 \text{ A}$
Rated dc link voltage	$V_{DC} = 720 \text{ V}$
Modulation type	Sinusoidal PWM
Switching frequency	$f_{sw} = 8 \text{ kHz}$
Input interface inductor	$L = 0.5 \text{ mH}$
Load inductor	$L_s = 0.5 \text{ mH}$
dc link capacitor	$C = 1430 \text{ } \mu\text{F}$
Displacement factor	$DF = 1$

The values of the circuit parameters are presented in Tab.1 and have been chosen in order to meet the IEEE Standard 519 requirement: line current THD (in steady state operation) <5%.

The input boost inductor is designed from the THD factor point of view.

Therefore, the input current THD factor is constrained to be less than 5% at the full load. The ac line inductance increases the commutation overlap angle, reducing the di/dt and the active filter bandwidth requirements. The boost inductor limits the peak switching currents to an acceptable value and smoothing the line current. A rigorous approach to the calculation of the converter filter inductor and capacitor for a given set of the above specifications is very complex. The input current harmonic distortion depends entirely on the system parameters and settings (e.g. the interface inductor, the switching frequency, the DC bus voltage, the input line voltage, current regulator bandwidth etc.) and the type of voltage modulation technique used. At the same time, the DC link capacitor design is tightly related to the system parameters, in particular to the value of input inductor, and settings (e.g. the maximum DC link voltage variation for rated power). In order to simplify the design of the circuit passive components, simplified semi-empirical relations based on [6], [8], [9] have been used.

3. OPERATING PRINCIPLE

The basic principle of Shunt Active Power filter is that it generates a current equal and opposite in polarity to the harmonic current drawn by the load and injects it to the point of coupling, thereby forcing the source current to be pure sinusoidal. As a consequence, the characteristics of the harmonic compensation are strongly dependent on the filtering algorithm employed for the calculation of load current harmonics (i_{cd}^* , i_{cq}^*). The implementation of current regulators has been performed by PWM-controlled Voltage Source Inverter (VSI) with capacitive energy storage at the DC side. The inverter switches are operated in a manner which forces the source current to follow whatever shape is necessary such that the total load current drawn by the filter and the nonlinear load is of

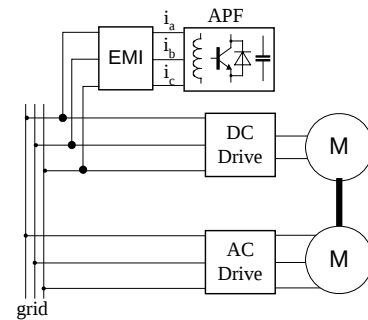


Fig.1: APF experimental setup

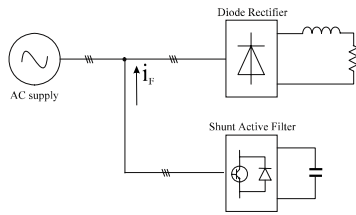


Fig.2 APF experimental setup

the correct magnitude and of the same shape as the input voltage. Initially the capacitor is charged through the uncontrolled rectifier formed by the diode in antiparallel with each controllable switch. A fundamental issue for shunt active filter design is the selection of a compensation strategy; that is, the procedure for evaluating the reference compensating current. As it is known, active power filters are used for compensating the

reactive power and the low-order current harmonics generated by a non-linear load. The maximum harmonic order that an active filter is able to compensate determines the filter bandwidth.

4. APF CONTROL

Both the active power filter current reference terms (i_{cd}^* , i_{cq}^*) are obtained from the nonlinear load current harmonics (Fig.3).

The Instantaneous Active and Reactive Current Component i_d - i_q [7],[12] or Synchronous Reference Frame algorithm is based on the Park transformations, that is, the three-phase system is transformed from a stationary reference frame into synchronously rotating components. Therefore, the active and reactive components of the system are represented by the direct and quadrature components, respectively. The transformation angle θ is sensitive to voltage harmonics and unbalance. The main advantages of this transformation are the followings: (i) fundamental-frequency current components are transformed into dc quantities; (ii) the instantaneous power can be independently controlled through the two separated current loops.

The performances of the various active filter configurations in steady-state and transient operating conditions are based on the current regulation quality. Thus, the d - q transformation is entirely justified. From the high pass filter outputs, the high-order harmonics remain in the signals. These are the undesired components to be eliminated from the system and they represent the reference harmonic current (i_{cd}^* , i_{cq}^*). The APF d -axis current reference term is function of the desired displacement factor (DF). In case of reactive power compensation, the d -axis high pass filter should be eliminated (Fig.3).

A proportional-integral (PI) controller performs the voltage regulation on the VSI dc side. Its input is the capacitor voltage error. The voltage controller block provides the amplitude command for the current, i_{cq}^* , to be maintained in the boost inductor. By using the dc voltage regulator, it is possible to control the active power flow in the VSI and thus the capacitor voltage. If the transient response is taken into consideration, the loop bandwidth will be as large as possible. But if the bandwidth of the voltage loop was large, it would undesirably modulate the input current. That is way, a bandwidth of about 70 Hz is a good compromise between the two conflicting requirements. The converter reference currents, i_{Fd}^* and i_{Fq}^* , are obtained from the dc voltage regulation and harmonic current generation system presented in Fig. 3.

The q -axis current term (i_q^*) is necessary to keep the dc link voltage (V_{dc}) constant (Fig.3). The q -axis current reference term (i_{Fq}^*) is also increased by the q -axis current term (i_q^*). The reactive power flow may be controlled by the first harmonic longitudinal current, i_d^* . Therefore, the current i_d^* is set to zero. Three-phase filter currents i_{FA} , i_{FB} , and i_{FC} are measured and transformed into the synchronous reference frame (d - q axes). The active filter current components i_{Fd} and i_{Fq} are then compared to the references: i_{Fd}^* and i_{Fq}^* . The current errors are fed into the PI regulators to apply the reference voltages V_{Fd}^* , V_{Fq}^* for the active filter inverter. By using the direct Park transformation the required three-phase active power filter voltage commands, V_{FA}^* , V_{FB}^* , and V_{FC}^* are obtained. The adequate switching states are generated for the corresponding power such that the input current is sinusoidal and in phase with the ac-side voltage in the whole load range.

The current loop response should be fast enough so that the input current tracks the reference current with a minimum error. This requires that the low frequency gain of the current loop should be large and the loop should have a large bandwidth. Figure 3 shows the block diagram of the SRF based controller implemented for the harmonic active power filter.

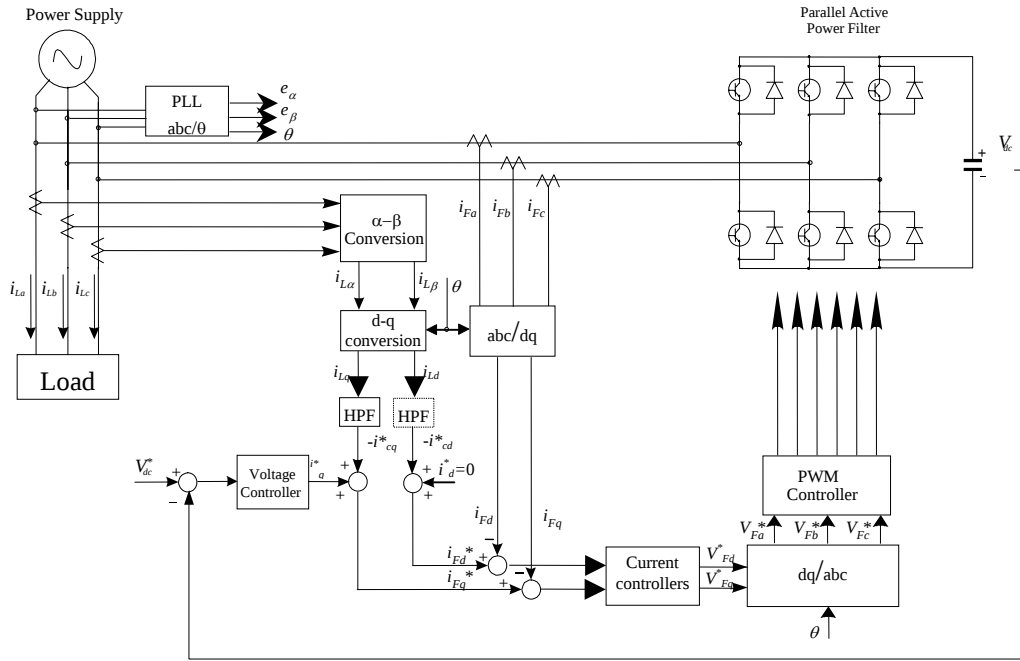


Fig. 3: The block diagram of the SRF based controller for the active power filter.

The phase-locked loop (PLL) is necessary for d - q axes synchronization with the grid reference voltage. The PLL tracks the grid frequency, ω , and the instantaneous voltage vector angle, θ , is obtained [13], [14]:

$$\theta = \arctan \frac{e_\beta}{e_\alpha}, \quad (1)$$

in which e_α and e_β are the grid voltage components in the stationary frame (α, β).

The three phase source voltage and the three phase load currents are transformed in the α - β reference frame through the following equations:

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (3)$$

The transformation of the stationary reference frame into the synchronous one is based on the following equation:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \cos \omega t & \sin \omega t \\ -\sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix}, \quad \omega t = \theta \quad (4)$$

Instantaneous active and reactive load currents i_{Ld} and i_{Lq} are decomposed into oscillatory and dc terms:

$$i_{Ld} = \tilde{i}_{Ld} + I_{Ld} \text{ and } i_{Lq} = \tilde{i}_{Lq} + I_{Lq}. \quad (5)$$

The currents that should be compensated are obtained by eliminating the dc current components using high pass filters (HPF):

$$i_{Cd}^* = -\tilde{i}_{Ld} \text{ and } i_{Cq}^* = -\tilde{i}_{Lq}. \quad (6)$$

Finally, the active filters' reference voltages are obtained by using:

$$\begin{bmatrix} V_{FA}^* \\ V_{FB}^* \\ V_{FC}^* \end{bmatrix} = \begin{bmatrix} \cos \omega t & -\sin \omega t \\ \sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} V_{Fd}^* \\ V_{Fq}^* \end{bmatrix}. \quad (7)$$

5. EXPERIMENTAL RESULTS

In the active power filter design, the voltage rating of IGBT devices is 1200V and the reference DC link voltage is set to $V_{dc}^* = 720V$. The maximum DC link voltage variation for rated power step is allowed to be 30V. From the aforementioned specifications, the DC bus electrolytic capacitor has been selected $C = 1565 \mu F$. For a sinusoidal PWM modulation, the three-phase input inductor parameters are $L = 0.35 mH$, $R = 0.001 \Omega$. The APF system test set-up is shown in figure 1. It contains a SIEI SpA inverter (AVy) which supplies an ac machine mechanically coupled with a dc machine controlled by a converter (TPD). The APF is connected to the system so as to compensate the absorbed current harmonics of the dc motor. The main characteristics of the test setup are: the APF Rated power $S_N = 33 kVA$; the dc machine rated power $P_N = 146 kW$; the ac machine rated power $P_N = 110 kW$. In ac drives, the dc capacitor magnifies the line harmonics. Harmonics of ac drives become more severe when the load is lighter. Under this circumstances the tests were done at 13,7% from the full load.

In order to test the results obtained by using the design approach, extensive experimental measurements have been performed on an APF sample unit in steady state. For the numerical implementation, a sample time of 125 μs has been considered. The experimental results are shown in Figs. 4-6. The switching frequency is 8 kHz for the scheme with PWM modulator. The current loop cut-off frequency is 1000Hz. It should be noted that the performance can be further improved by properly adjusting the parameters of the dc voltage regulator.

Before the connection of the Active Power Filter, the load current had total harmonic distortion factor of THD = 57,7%. After the Active Power Filter connection the supply THD current factor becomes 4.9%.

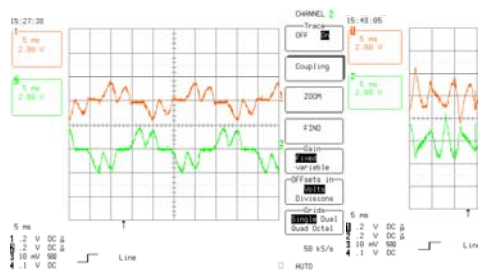


Fig.4 The load currents: IL_A (A-phase) and IL_B (B-phase) (50A/div).

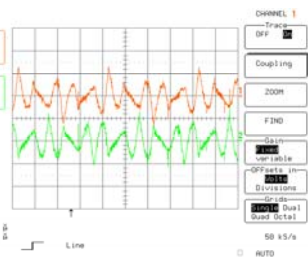


Fig.5 The compensated currents: IF_A and IF_B (25A/div)

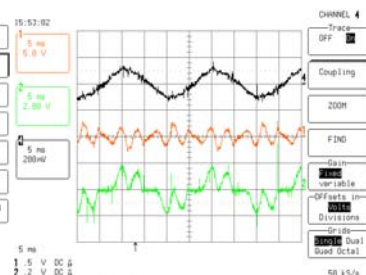


Fig.6: Experimental results of APF with diode bridge load using SRF based control structure. From top to bottom: line current, APF output current and load current (50 A/div, 5ms/div)

The results presented in Fig. 6 confirm that for Synchronous Reference Frame algorithm, the line current attains a 4.9% total harmonic compensation under balanced and sinusoidal voltage conditions.

6. CONCLUSIONS

The APF permits to improve power quality of the AC distribution systems. The APF considered in this paper is shunt active filter and acts as harmonic current compensator. An active power filter laboratory prototype was built and tested to establish feasibility of the approach. Selected experimental results are provided herein. The control design has been successfully implemented and tested using the SRF approach. The main advantage in using SRF as control strategy is that is a well-known approach in the motor drives industry (vector control applications). The active power filter control was implemented and tested in a fixed-point digital signal processor dSMC 101. The inner current loop has high bandwidth, which is necessary to achieve wave shaping of the input current. Due to their high bandwidth requirement, their applications are limited to nonlinear loads below 10 MW [5]. Experimental work has been conducted for the APF both for the steady-state and dynamic operating conditions. An APF system for a 146 kW rectifier load at an industrial site is also given to illustrate its application. The experimental results show that the magnitudes of harmonic components are considerably reduced in the AC mains. The total harmonic distortion of this current is decreased from 57,7% to 4.9% with the active power filter. The test results confirm that the developed prototype represents a reliable APF converter for line current harmonic compensation in order to meet the IEEE standard 519 in three-phase utility interface of power electronic loads. Since the share of converter loads in industrial power systems is increasing will continue enlarging perspectives of applications to the APF's.

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